

The calorimetry at the future e^+e^- linear collider

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I. INTRODUCTION

The physics programme for an electron-positron linear collider with center of mass energy ranging from 90 GeV to 800/1000 GeV, is largely dominated by events with final state containing many jets [1] (essentially di-boson events with W,Z or Higgs decaying into jets). For an experiment on such an accelerator, the goal of the calorimeter can be either to measure well the total flow of energy (in jets) or to measure the photons, the neutral hadrons and to identify the leptons e , μ or τ . The second option seems more difficult, but our contention is that its three items can be optimised together and that, by that time, the energy flow measurement is optimised far beyond the first solution capability. This is done through a so-called energy flow algorithm which employs not only the calorimeter but also the tracker. The studies described below use a full simulation of the calorimeter named Mokka [2] based on GEANT4.

II. PHYSICS PROGRAMME AND CALORIMETER PERFORMANCE

First we can review the impact of the jet resolution on the physics programme: This point has been looked at for few reactions up to now and needs a lot more work to assess it properly.

Parametrising the jet energy resolution as $\Delta E_{jet} = \alpha \sqrt{E_{jet}}$, two possibilities have been used, one with $\alpha = 0.6$ corresponds to a slightly improved LEP calorimeter, the other, with $\alpha = 0.3$, corresponds to what has been obtained in a full simulation and reconstruction with the Si-W electromagnetic calorimeter and the digital hadron calorimeter described in the TESLA TDR [3].

First, the reaction $e^+e^- \rightarrow Z H H$ which appears as 6 jet events. For an integrated luminosity of 1 ab^{-1} , the signal is observed at 3 sigmas for 0.6 and at 6 sigmas for 0.3, the difference between missing or getting it [3].

A way to measure the impact of the resolution is to consider the amount of statistics, running time, needed to obtain the same significance. In the case of $e^+e^- \rightarrow ZH$ with Z into $q\bar{q}$ and H into WW^* , going from 0.3 to 0.6 corresponds to loosing 45 % of luminosity [4]. In the same way, when separating $ZZ\nu\bar{\nu}$ from $WW\nu\bar{\nu}$ the loss is of 40 % of luminosity. This is illustrated in figure [1]. The impact on the measurement of the process $e^+e^- \rightarrow t\bar{t}H$ is under consideration. Considering the cost of running and the impact on physics of diluted runs this is impressive. It has nevertheless to be studied with full simulation and reconstruction and extended to many more reactions.

III. THE ECAL DESIGN

Now that the physics case is painted, we can recall the basics of the analytical energy flow. The energy flow of a jet, or a system of jets, is written as the sum of its components $P = P_{Ch.\text{particles}} + P_\gamma + P_{h^0}$ (h^0 for neutral hadrons). The argument is as follows: the charged hadrons make about 60% of the jet energy and, being of rather low energy, are much better measured in the tracker than in the hadron calorimeter. This point has to be tempered when taking into account the track reconstruction efficiency, the generation of fake tracks, the decays of particles like K^0 . Such a method relies more on separating properly the particles than on the intrinsic energy resolution. To get it, the calorimeter has to be far enough from the interaction but inside the coil, has to have a small radiation length, a small interaction length and a matched read-out granularity. Compact and granular.

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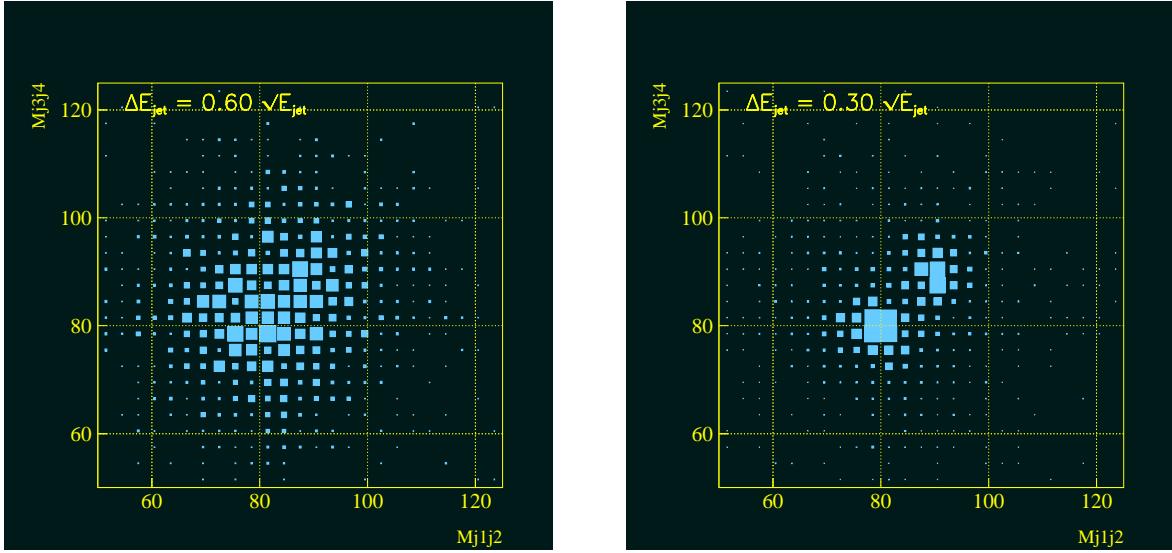


FIG. 1: Impact of the jet energy resolution on the WW/ZZ separation, when α (see text) goes from 0.6 (left) to 0.3 (right).

There is one implicit parameter, the ratio of radiation to interaction lengths. To measure properly the photons and to identify the electrons we need to separate the electromagnetic and the hadronic primary components. This is currently achieved up to a certain level longitudinally by going for a large ratio of radiation(L_{X0}) over interaction lengths (λ_I). We can compare the values for the iron, the tungsten and the lead.

material	λ_I (cm)	L_{X0} (cm)	λ_I / L_{X0}
Fe	16.8	1.76	9.5
W	9.6	0.35	27.4
Pb	17.1	0.56	30.5

The need of containing properly enough high energy electromagnetic showers drives us to about 24 X0. This is not extremely sensitive since the longitudinal size grows logarithmically with energy and that we still get information from the hadronic calorimeter behind. Clearly we desire an electromagnetic calorimeter with a tungsten radiator and a very compact detecting medium providing the adequate granularity, a size close to the Molire radius. The only solution known by the authors is silicon diodes. A clear obstacle seems to be, more than the technical difficulty, a question of money. This will be discussed more thoroughly later.

The final parameters of the electromagnetic part we are left with are then:

- The radiator sampling or equivalently the number of layers. This drives the intrinsic energy resolution and concurrently the price. We have considered 40 layers to reach a resolution close to 0.1, but, if we really care only of jet resolution, 20 may be enough as presented later.
- The cell size which provides the separation and the number of channels. It has to be noted that a huge number of channels is a real technical challenge but has little impact on the price, driven by the silicon area. Currently we consider 1 to 1.5 cm².

IV. THE HCAL DESIGN

The same type of arguments, number of interaction lengths inside the coil, the shower size, leads to compactness and favour tungsten. Reasons of cost, of mechanical structure, and may be some lack of reflection, have lead to choosing for the current design stainless steel for radiator, the eddy currents generated by a magnet quench prohibiting copper. The structure is then 40 layers of 2cm thick iron plates equivalent to 4 λ_I . In fact this has to be worked out again playing with the λ_I / L_{X0} ratio and with the thickness. A hadronic shower can be seen as hadronic tracks connecting photon showers (π^0). Playing with λ_I / L_{X0} will change the occupancy of the electromagnetic subshowers with respect to the global hadronic shower. Reducing λ_I will enhance the ability to separate the showers, but, for a given interaction length sampling, will degrade the resolution. An example is shown on figure 2 where the same jet is seen in iron and in "expanded tungsten". This is tungsten

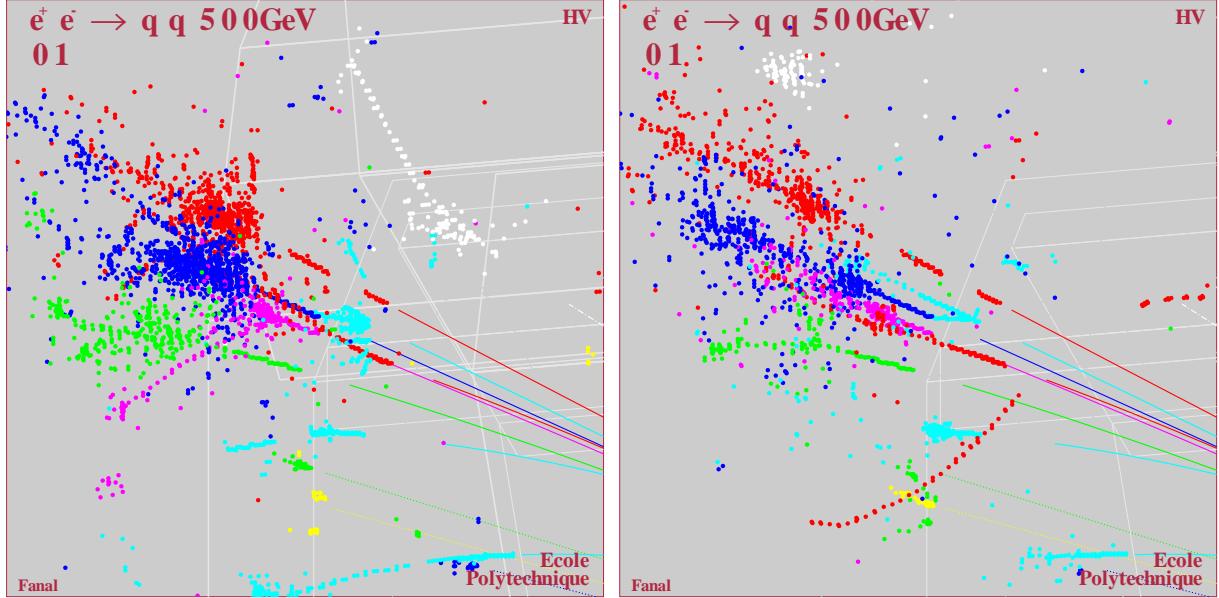


FIG. 2: The same di-jet for a digital-steel (left) or for a digital-tungsten (right) HCAL

where the density has been modified to get the same fraction of interaction length in a plate as in the standard iron plate.

We need now to focus on the hadronic cell structure. There are two approaches, one, global, will match the cells to the hadronic shower width, the second tries to take advantage of the tree structure of the shower and plays the same game as the electromagnetic part, trying to isolate the electromagnetic component from the hadronic tracks. In the first method the energy collected in a cell has to be measured, in the second you would just basically continue the ECAL, the cost precludes such a solution but it happens that, for a proper granularity, a simple counting of the cells provides linearity of the response and an adequate energy resolution.

These two solutions correspond grossly to the two variants of the TESLA TDR, the variant with scintillator tiles varying in size between 5 and 20 cm, [5], and the so-called digital variant with 1cm^2 cells.

We can develop on the more original variant, the digital. Here the spatial information is preferred to the local energy measurement. The detecting medium is read in small cells, about 1cm^2 which may make some 50 millions cells, but purely by yes/no. This provides an optimal information for separating the showers, hence an excellent muon identification in particular below 5 GeV where muon chambers are useless. This clearly provides also an easy way of handling halo muons. Then we can wonder about the jet energy resolution. This has been looked at with a simulation where the detecting medium is a perfect scintillator structured in 1cm^2 cells. Pions of different energies are sent. The energy seen in the cells is summed, the number of cells is counted and also a neural net trained for energy resolution out of the cell distribution is used. Figure 4 shows the response as a function of energy.

It is clear that, for this size of cell with that sampling, the counting provides a better estimate of the energy than summing the cell energies. This a priori surprising result originates from the suppression of cell fluctuations by the counting. The jet resolution has been investigated at the Z peak leading to a resolution of 2.89 GeV as shown on figure [3], equivalent to an α of 0.3.

The main advantage of the method is nevertheless in the shower separation and has to demonstrate its power with boosted events. For that purpose, reactions like $e^+e^- \rightarrow W^+W^-$ at maximum energy (800 GeV) are under study. This is illustrated in figure 5 showing a W dijet in the view that best separates the jet components.

V. AN AFFORDABLE CALORIMETER

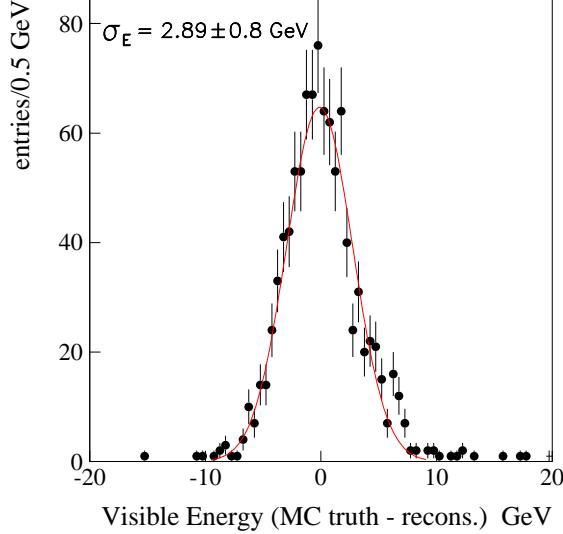


FIG. 3: The visible mass resolution for $q\bar{q}$ Z decays at rest.

A. The W-Si electromagnetic calorimeter

The more frequently asked questions about the ECAL are:

- Is it affordable ?
- By how much the performance is sensitive to the silicon diode quality ?
- Does the number of channels (about $35 \cdot 10^6$) create specific problems for the calibration, uniformity,etc...

The questions of the silicon diodes quality

First, to simulate dead wafers, a fraction, up to 5%, of the wafers are not used in the reconstruction code . It is assumed that there is no geometrical correlation between the dead wafers. Because there is a good knowledge of the shower profile, (related to the number of layer), an efficient correction can be applied on the reconstructed photon/electron when there is dead wafer(s) in the shower path. As a consequence, the performances of the ECAL are alsmost unchanged; i.e. the energy resolution at 1 GeV grows from $10\%/\sqrt{E}$ (no dead wafer) to $10.2\%/\sqrt{E}$ (5% of dead wafers). It is important to note that accepting 5% of dead wafers in the production, may increase the industrial yield by a factor of 2 [6], which directly changes the overall cost of the ECAL by roughly the same amount.

The total area of silicon

A second test has been performed by changing the number of silicon layers from 40 (TDR) to 20. Using the deposited energy, the stochastic term of the energy resolution increases from 10% to 14%, but using in addition informations like the pad multiplicity, the shower profile,etc..., leads to a stochastic term of 12%. To see the impact on jets, the photon reconstruction code PFD04 [7] has been adapted to the 20 layers geometry. The result, on figure 6, given in terms of the energy resolution on the photonic component of the jet energy, is an increase of only about 10%. Clearly, the case for the silicon-tungsten ECAL is largely unchanged when reducing the number of layers from 40 to 20, which almost reduces the overall cost of the ECAL by a factor two.

A very large number of channels

The total amount of readout pads in the ECAL is about $35 \cdot 10^6$. This very large number induces strong constraints on the level of the noise in the readout, the electronics cost,etc... It can also generate problems with the calibration, the non-uniformity,etc... The overall calibration is not a problem with the large number of processes involving electron(s), where the tracker can provide the momentum of the electron(s). It remains the intercalibration and more generally the effect of the non-uniformity of the detector. The main sources of non-uniformity are i) the electronics gains, ii) the depletion thickness of each diode and iii) the thickness/density

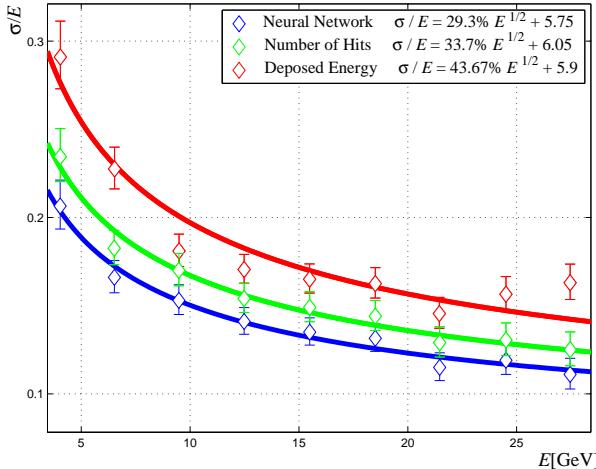


FIG. 4: The energy resolution using energy deposited in the scintillator(red dots), using pad multiplicity(green square) and eventually using more informations from digital pattern (blue triangle).

of the tungsten. It has been pointed out previously [8] that all these sources could be controlled, on-line for the point i) and at the production or construction time for the points ii) and iii). The residuals on the correction would come from the errors on the measurements. Under this condition, the type of distribution we expect for the dispersion is gaussian. Therefore, to do the study, the pad responses have been smeared by a gaussian centred at zero with a dispersion of 2% and then of 5%. The resolution on the final state photons in jet events increases by only 70 MeV for a non-uniformity of 5%, a value which seems largely within reach. The main concern remains the coherent noise, which will be studied by prototyping.

The question of the cost

Summarizing informations on the question of the cost of the ECAL, when compared to the LHC microstrip tracker or pre-shower, it can be stated that :

- the macroscopic size of the silicon detector (1cm^2) leads to an easier production;
- the number of masks to produce the silicon matrices is about 2 times smaller[6];
- the industrial yield should be 2 times larger;

In addition, if needed for the cost, the number of layers could be decreased by a factor 2, with only a modest degradation of the performances on jets. From all these points, the conclusion is that **the cost is not a killing factor for the silicon-tungsten ECAL**.

B. The digital hadronic calorimeter

When speaking of large area of possible digital chambers in recent experiment, the example of Belle detector[9], with 4000 m^2 of RPC's can be taken. As a matter of fact, the technical solutions for the detecting device are under investigation, in particular at IHEP-Protvino. The possibility to use RPC's or gas wire chambers makes the solution quite inexpensive and robust. The yes/no electronics makes even such a large number of channels inexpensive. There is still much work to be done.

A full description of the mechanical and electronic solutions for the W-Si ECAL as well as for the two options of the HCAL can be found in the TDR [3] and at the CALICE web site [10].

VI. CONCLUSIONS

The electromagnetic calorimeter as a sandwich of tungsten and silicon appears to be adequate from the point of view of physics, it remains to be fully proven technologically. As described in the TDR it may look financially difficult but compromises are possible which do not harm deeply the physics performances and reduce very substantially the cost.

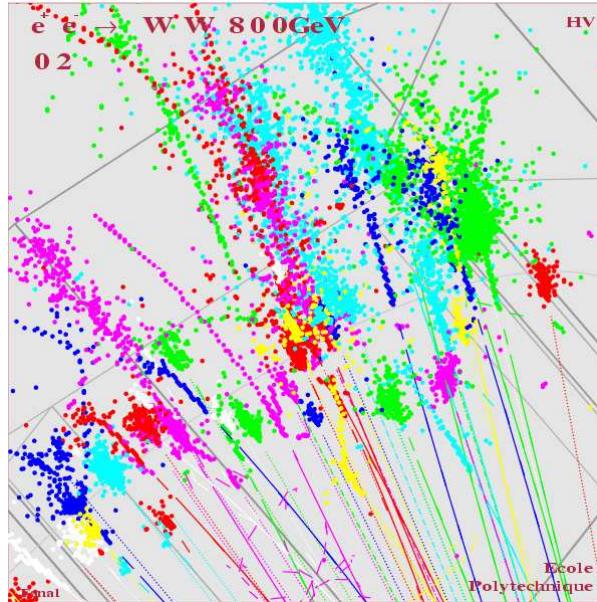


FIG. 5: View of W di-jet in $e^+e^- \rightarrow W^+W^-$ at $\sqrt{s}=800$ GeV

For the hadronic part a choice has to be made between the two variants and will be made on the basis of full simulation and reconstruction as well as some prototyping. Nevertheless, aside that point, many parameters have to be tuned properly like the choice of radiator material.

Mastering the design of a calorimeter for a linear collider needs still considerable effort on the technical side but also on the software development and on the physics validation of the performances.

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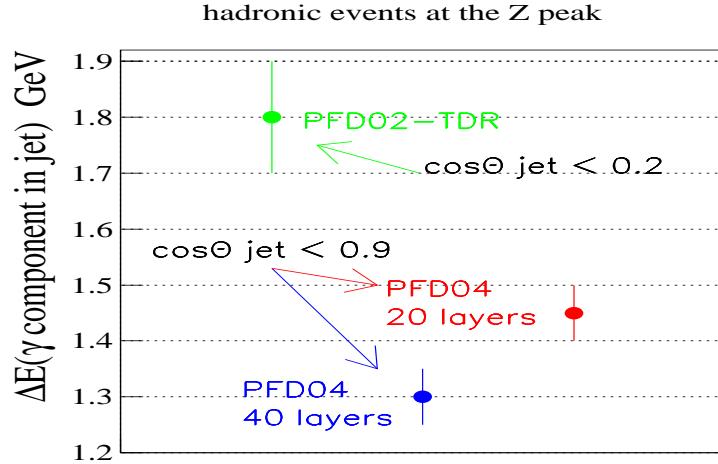


FIG. 6: The resolution on the photonic component of the jet energy. The value of the TDR (green dots) is compared to the new version of the photon reconstruction code for 40 (blue dots) and 20 (red dots) layers of silicon.